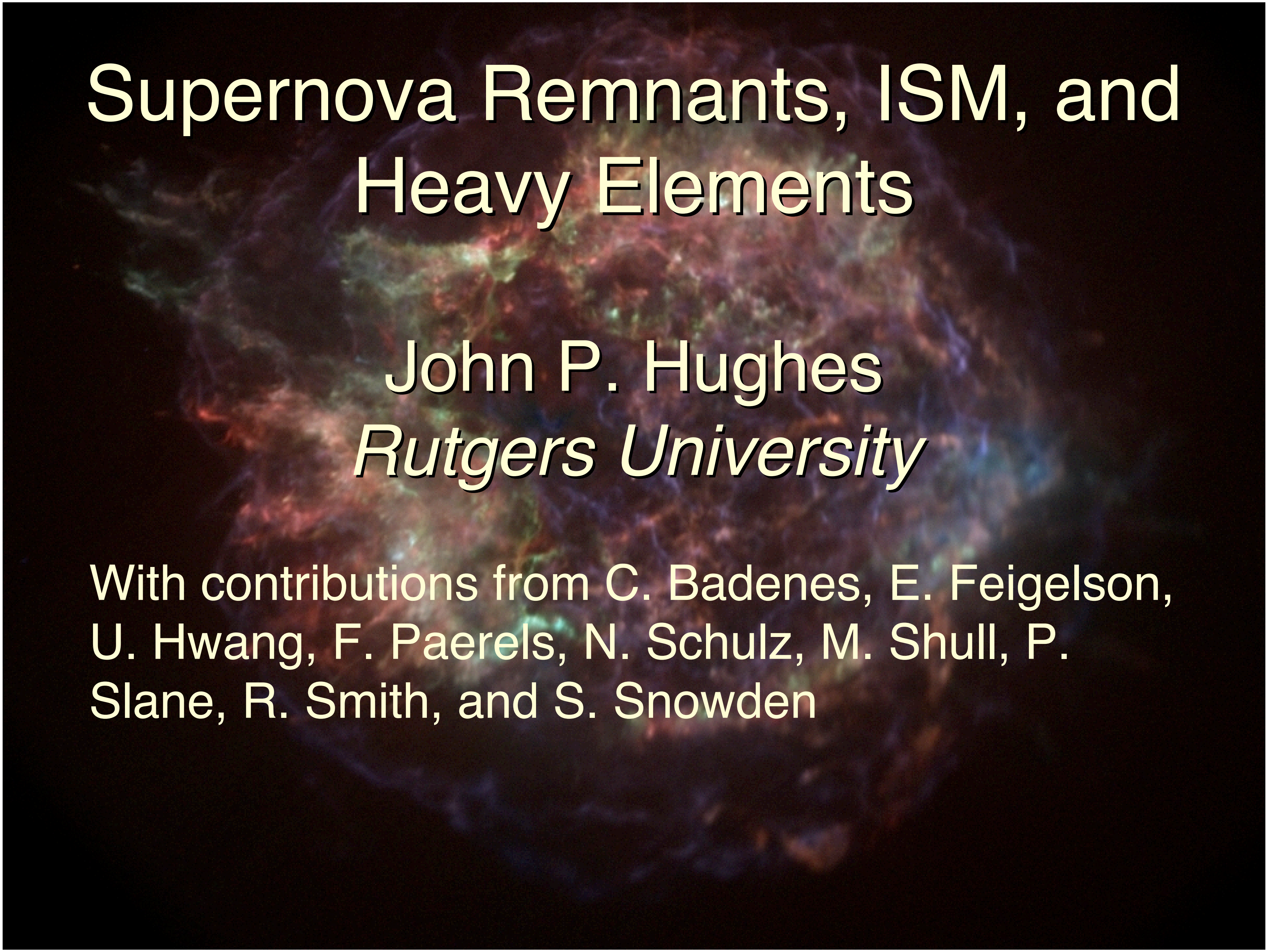


Supernova Remnants, ISM, and Heavy Elements

John P. Hughes
Rutgers University

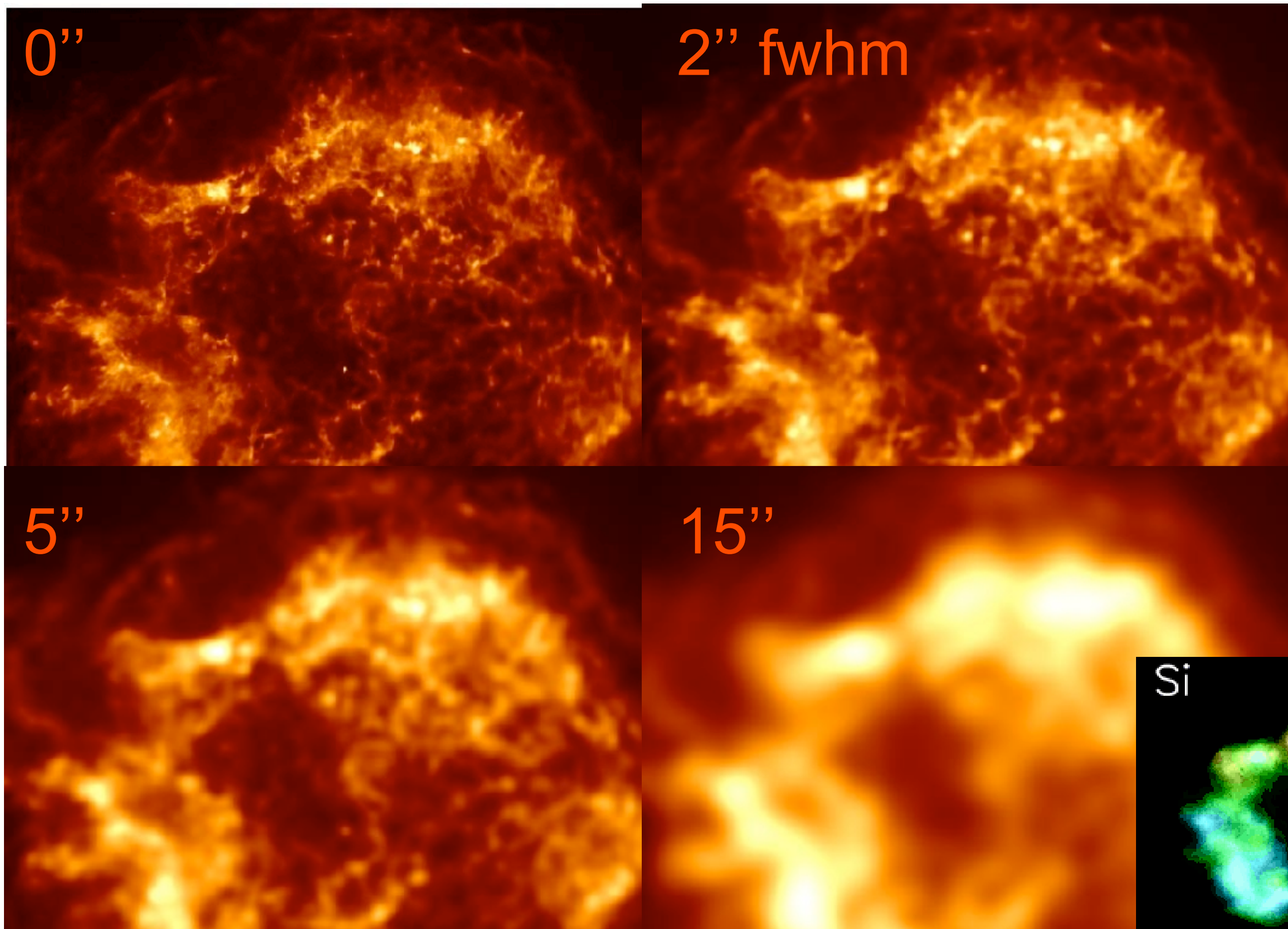
With contributions from C. Badenes, E. Feigelson, U. Hwang, F. Paerels, N. Schulz, M. Shull, P. Slane, R. Smith, and S. Snowden

Questions to Con-X Panel

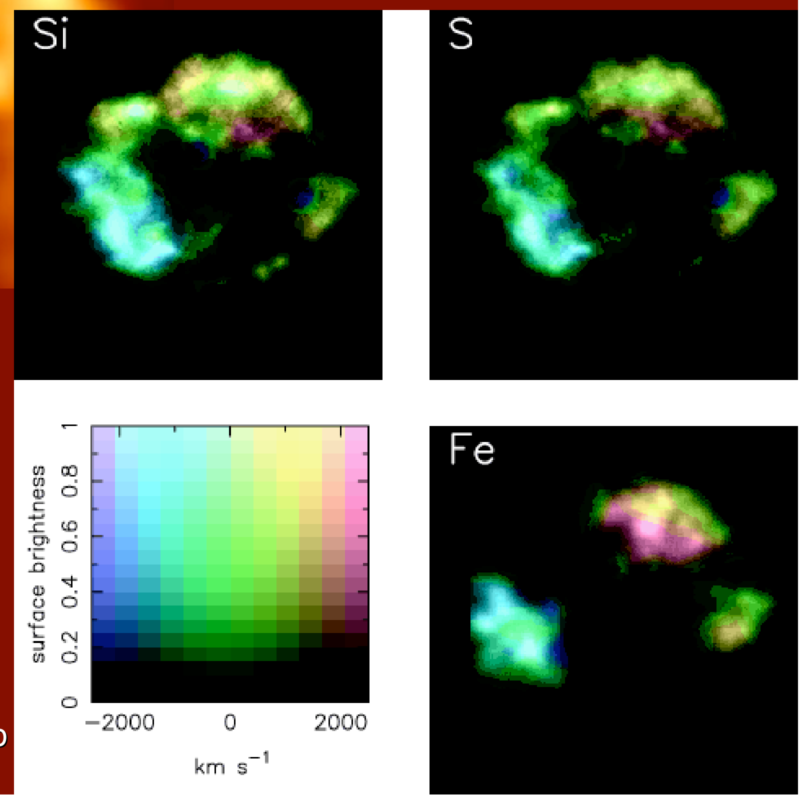
- How do core collapse supernovae explode?
  - What is the connection between CC SNe and gamma ray bursts?
- What is the physics of Type Ia supernovae?
  - Why, for example, is there a luminosity-light-curve-width relation?
  - Where does the ignition occur?
- What are the progenitors of Type Ia supernovae?
- What can we learn in detail about explosive nucleosynthesis by studying ejecta from individual SNRs?
- How will SN1987A evolve during the Con-X era?
- What is the nature of the X-ray emission from the Galactic ridge and bulge?
- What are the abundances of the ISM and how do they vary with position?
- What is the gas to dust ratio in the ISM and what are the properties of these constituents?

Core Collapse Supernova Remnants

- Focus on two important sources: Cas A and SNR 1987A
- Cas A: underwent extensive mass loss, reverse shock is now traversing inner, explosively synthesized Si and Fe ejecta (age 330 yr)
- SN 1987A: in process of transitioning to supernova remnant with emission behind forward and reverse shocks (age 17 yr)



Measured radial velocities in Cas A are between +/- 2000 km/s (Willingale et al. 2002)



Typical knot angular scales are 2-3”
Cas A knot spectroscopy requires at least 5” resolution: 2” is very desirable

Nucleosynthesis in Cas A

- Shocked ejecta of distinct composition and distribution in Cas A, primarily Si-group or Fe emission (Hughes et al. 2000). These were explosively synthesized near core of explosion. Explosion imprints mass composition, distribution, dynamics (Willingale et alo. 2002)
- Unique knottiness of Cas A's ejecta is a great advantage. Individual knot spectra can be interpreted with relatively simple models to make inferences about mass, shock history, explosion asymmetries (Laming & Hwang, Hwang & Laming 2003).
- CCDs have limited spectral resolution: errors on velocities are large and dominated by uncertainties in ionization fraction (Willingale et al. 2002).

Without Con-X (or XEUS), there is no study with both good angular *and* high spectral resolution.

Nuclear De-excitation Lines

- Fe synthesis (alpha-rich freezeout) traced by ^{44}Ti, which decays to ^{44}Sc with a 60-day half-life and then to ^{44}Ca.
- Nuclear de-excitation lines of these daughter nuclei have been detected in Cas A (flux 3×10^{-6} ph/cm^2/s:

  68 and 78 keV (^{44}Sc) Vink et al. (2001)

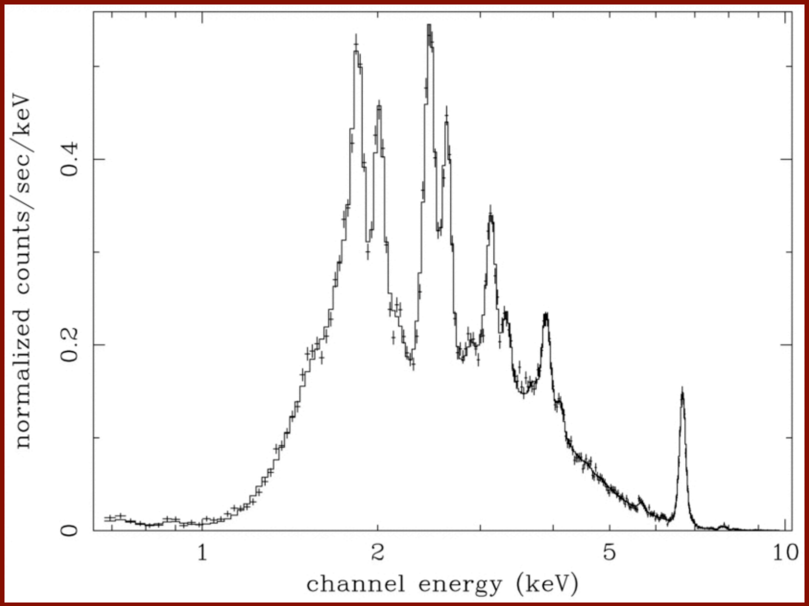
  1157 keV (^{44}Ca) Iyudin et al. (1994, 1997)

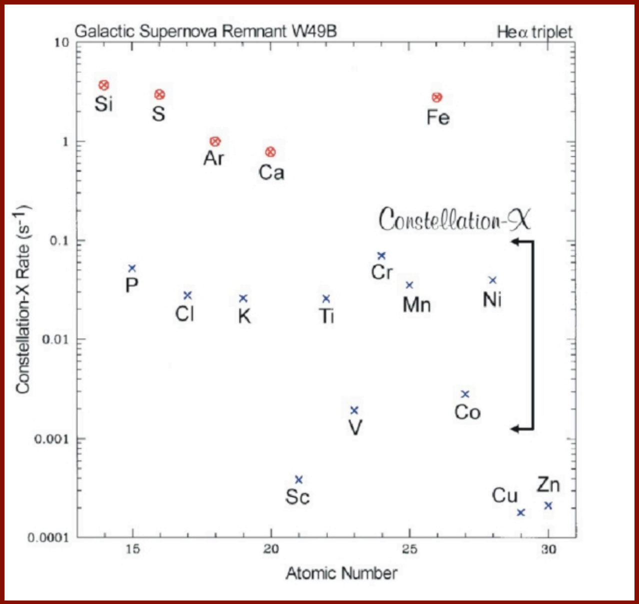
  - These lines are also expected in other core-collapse (and thermonuclear) explosions based on ^{44}Ti production (Diehl & Timmes 1998).
  - Measurement of any of these line fluxes gives the total mass of ^{44}Ti (and thus ^{56}Fe), shocked or not.

Would require energy coverage to ~100 keV

Trace Abundance Species

- High effective area and spectral resolution make the less abundant ejecta accessible to Con-X.
- Elements with energies below 10 keV and predicted masses between 10^{-5} and 10^{-3} M_{sun} (Rauscher et al. 2002) include: P, K, Ti, V, Cr, Mn, Co, and Cu.
- He-like and H-like line fluxes needed for diagnostics to constrain temperatures, ionization ages, masses.

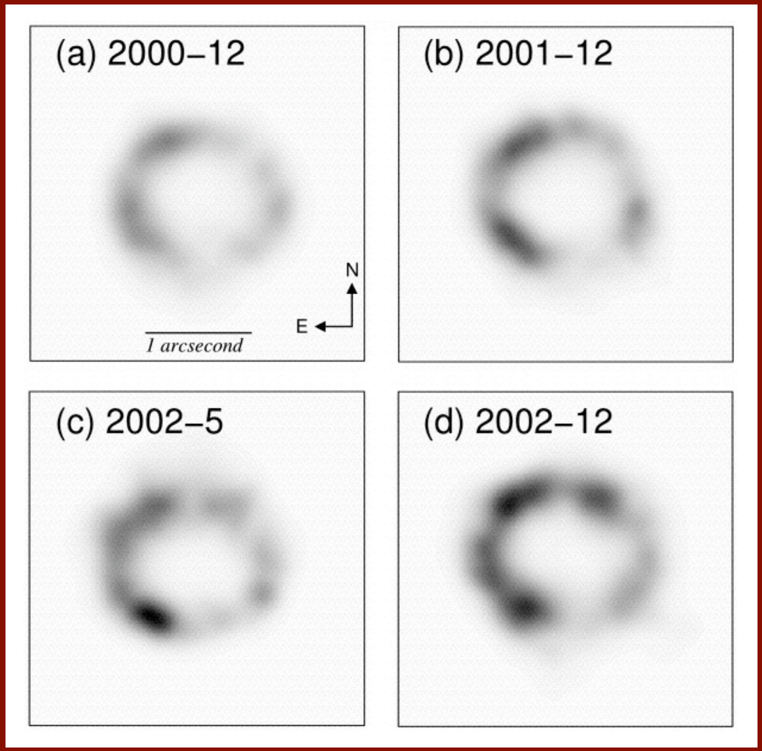


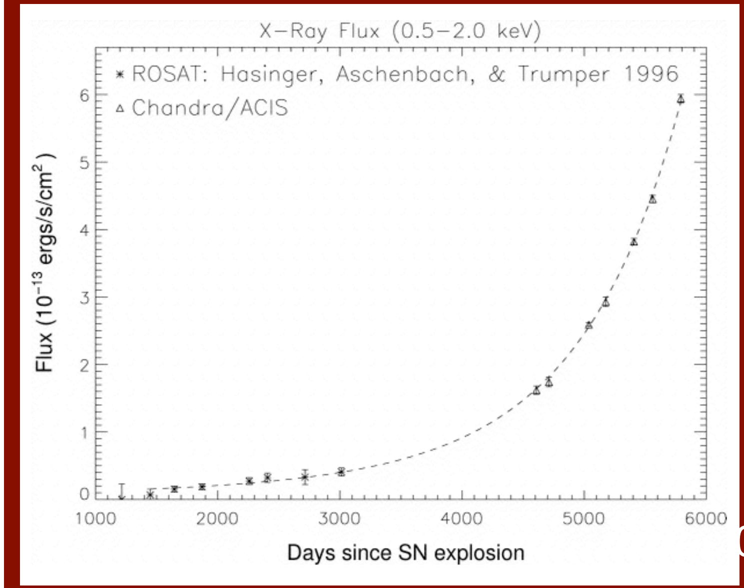


Evolution of SNR 1987A

Rapid brightening as forward shock encounters dense circumstellar ring

Brightening predicted to continue 10-100 fold over the next ten years (McCray)





03

Park et al. (2004)

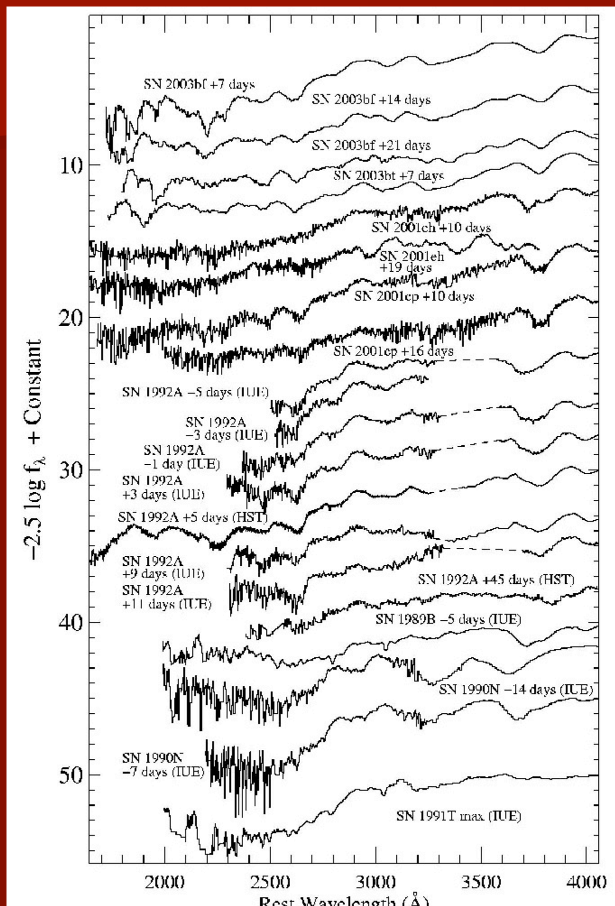
Onset of Reverse Shock into Heavy Elements in SNR 1987A

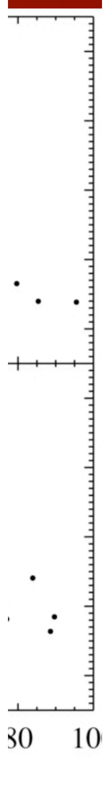
- Fe measured out to velocities of roughly 5000 km/s from SN light curve
- HST has observed H atoms crossing the reverse shock (Michael et al. 2003)
- At Con-X launch, the ejecta velocities into the reverse shock should be about 6000 km/s: the heavy element ejecta should cross the reverse shock during the Con-X era!
- Real-time radial mapping of the ejecta structure as knots cross the reverse shocks and emit X-rays

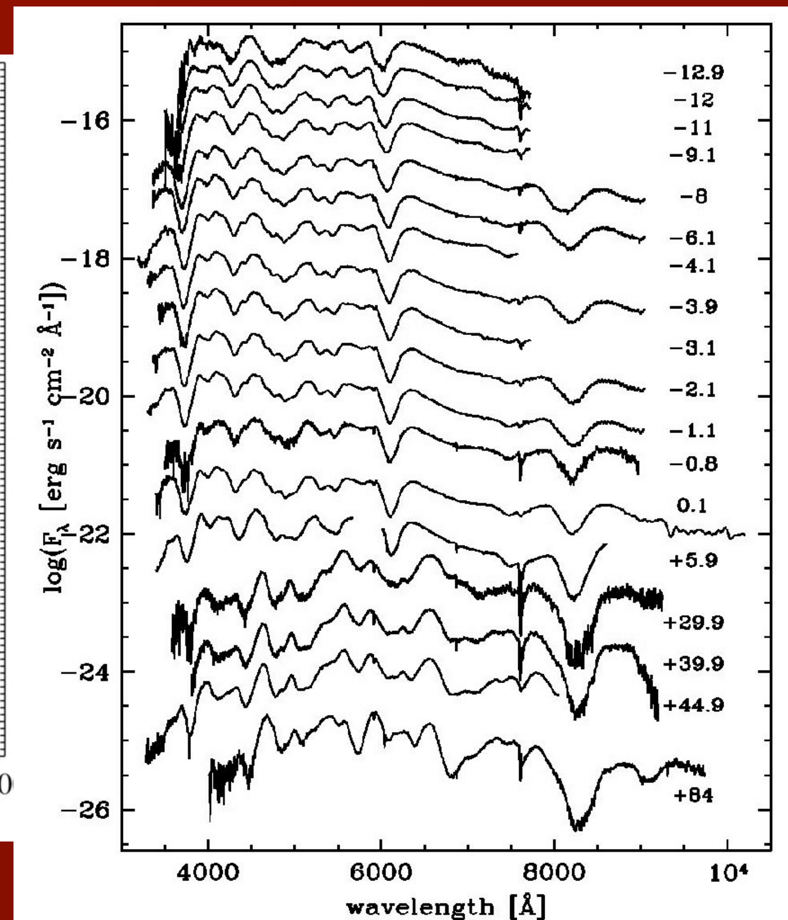
Thermonuclear (Type Ia) Supernovae

- What we know with some confidence
  - No hydrogen, a solar mass of ^{56}Ni, some intermediate mass elements (Si, S, O, Mg,…)
  - Occur in all galaxy types
  - Mean rate ~ 0.3 SNU
  - Light curves and spectra fairly homogeneous
    - variations correlate with 1 parameter – light curve width
- What we do not know
  - Precise progenitor system
  - Explosion mechanism

Optical Data on SN Ia







Light Curves

UV Spectra

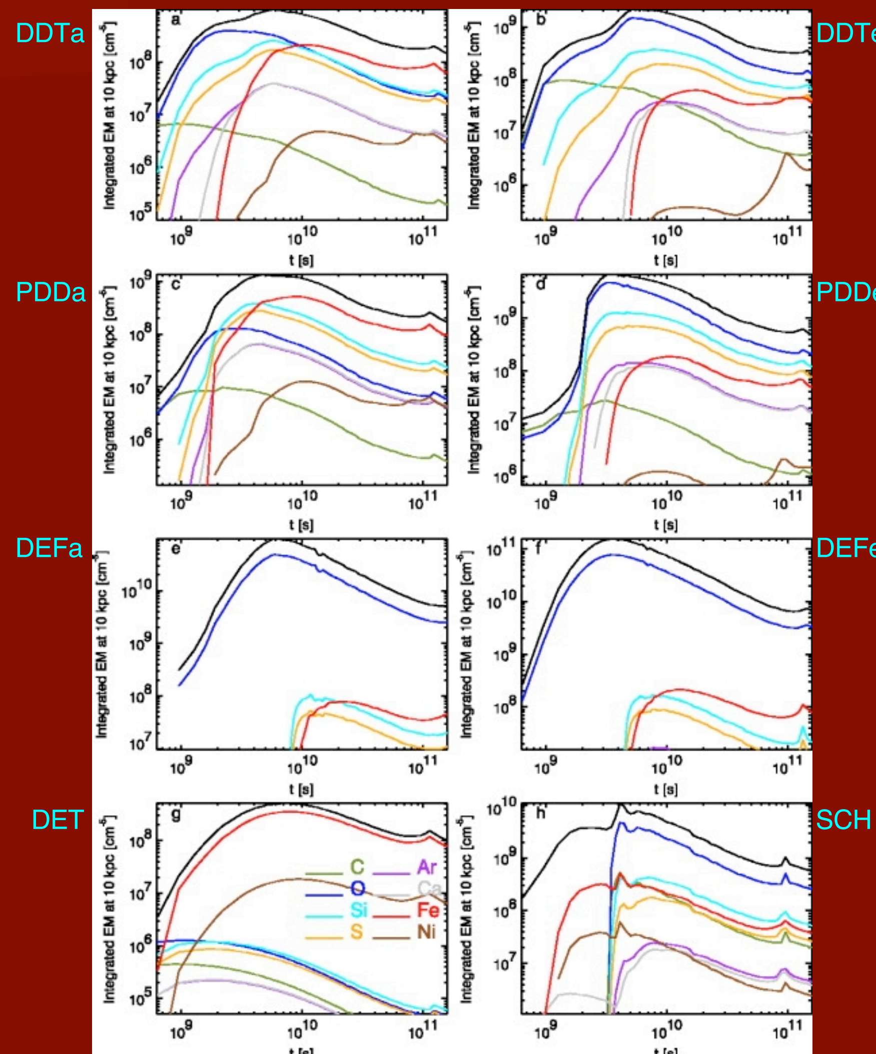
Optical Spectra

Prompt X-ray Emission from SN Ia

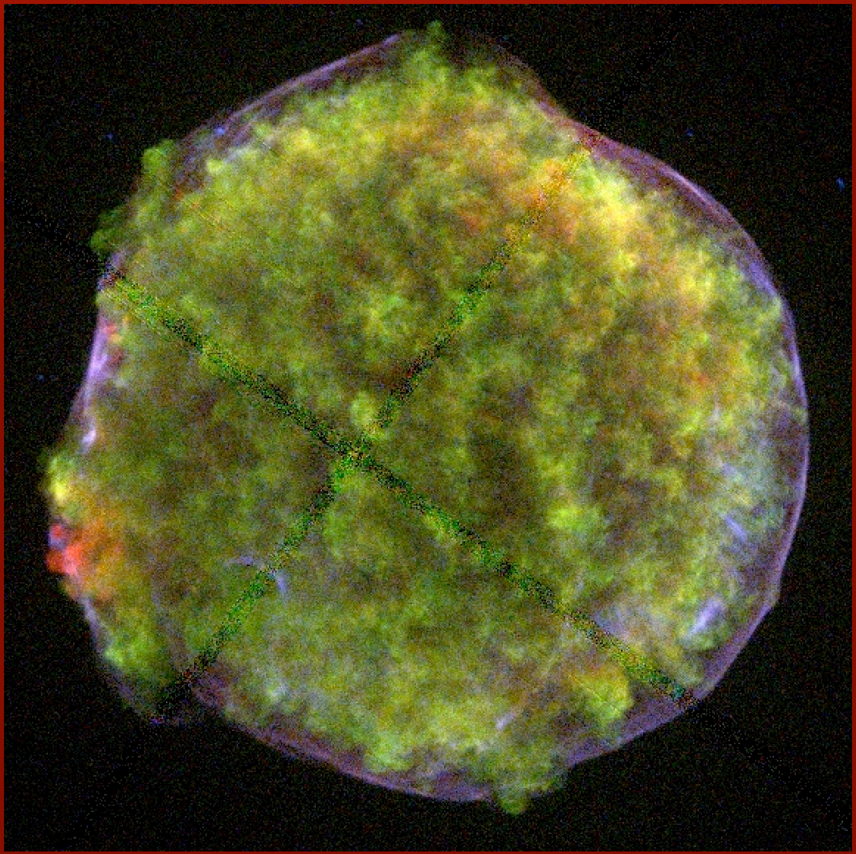
- Basic idea
  - Expect some CSM in system for single degenerate progenitor scenario
- No detection of CSM from normal SN Ia to date
  - SN 2002ic showed Hα but this was an unusual SN Ia
  - Optical limits are model dependent and line broadening makes detection difficult
  - Radio limits are subject to large uncertainties (efficiency for generating synchrotron radiation unknown; synchrotron self-absorption must be modeled)
  - X-ray data can be cleanly interpreted for gas density
- Chandra limits now ~10^{-15} erg cm^{2} s^{-1} (2-10 keV) in 20 ks
  - Con-X should get an order of magnitude deeper, which equates to a factor of 3 better sensitivity to the CSM density
  - Important to observe SN as soon after explosion as possible
    - Limit on mass loss rate of wind depends linearly on time
    - Current surveys can detect SN Ia at the distance of Virgo 2 days after explosion (~2 weeks before optical maximum)
    - Expect 1 bright SN (12-13 mag) per year
  - Statistics of 19 bright SN Ia (since SN1992D)
    - 11 northern:
      RA 0-6 hr 0, RA 6-12 hr 8, RA 12-18 hr 2, RA 18-24 hr, 1 (Virgo: 12.44h,12.72d)
    - 8 southern
      RA 0-6 hr 3, RA 6-12 hr 1, RA 12-18 hr 2, RA 18-24 hr, 2

Getting to the Physics of SNe Ia from Their Remnants

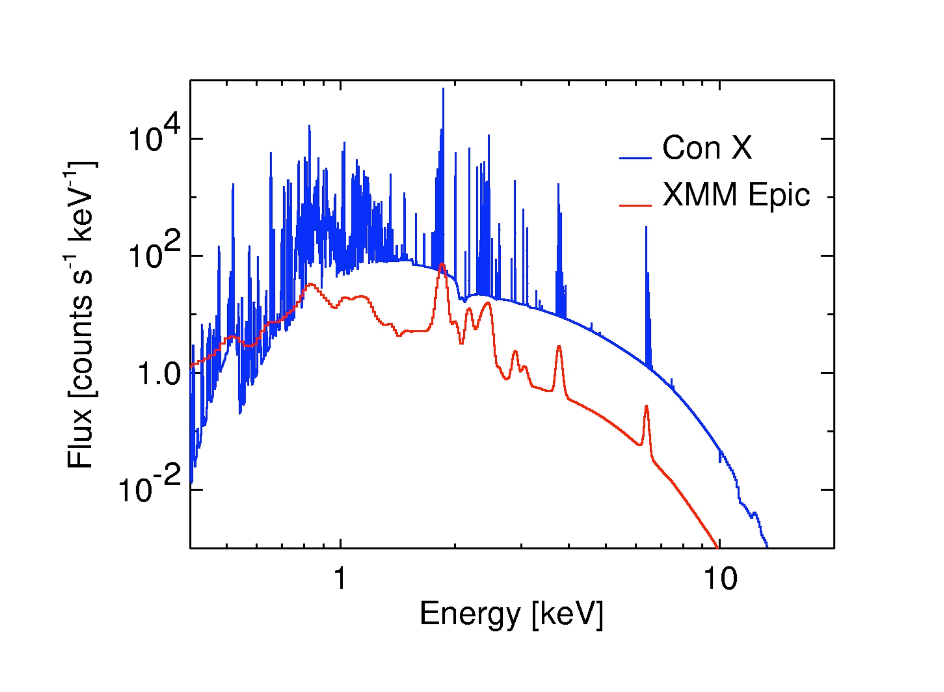
- Some variation in SN Ia explosion mechanism needed to explain light curves (e.g., density when flame speed transitions from deflagration to detonation)
- Strong compositional differences for different explosion types
- Manifested at different times during evolution of SNR (Badenes et al. 2003)
- Tycho, E0509-67.5, and DEM L71 X-ray spectra favor delayed detonation models



Tycho – Line Studies



9.5’ x 9.5’



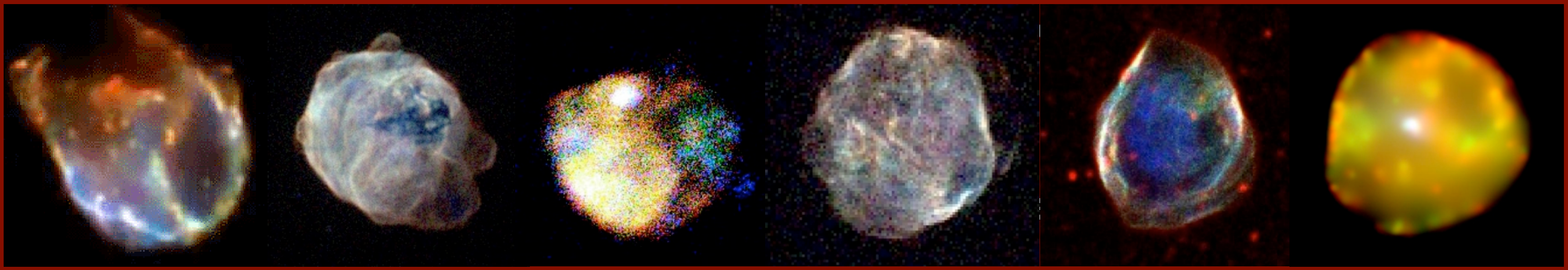
Velocity – key new info from Con-X/XEUS

Extragalactic SNRs

Ejecta-dominated remnants can only be seen for the first few thousand years, before they merge with the surrounding ISM (which may itself be enriched by the pre-explosion stellar wind).

Although there are more than 250 radio SNRs in the Galaxy, most are highly absorbed, and so perhaps only 20-50 Galactic SNR are even suitable for detailed study in the soft (0.5-2.5 keV) band.

Magellanic Cloud SNRs add another 30 or so objects for study.



SNRs in M33

- XMM surveyed M33 (d=795 kpc, 1" = 3.9 pc) found 44 confirmed and candidate SNR, down to a limiting luminosity of 10^{35} erg/s, or 10^{-15} erg/cm^2/s (Pietsch et al. 2004)
- At the flux limit of 10^{-15} erg/cm^2/s, 100 ksec with Con-X will yield about 600 counts (between 0.2-2 keV)
- How well can Con-X do on the brightest sources?
  - Assuming 2 eV resolution for Con-X, between 0.5-2.5 keV there are 1000 resolution elements, so ~ 3σ/bin is ~10 counts/bin or a 10,000 count spectrum.
  - In 100 ks with Con-X, 11 SNRs in M33 are bright enough to yield this kind of spectrum
  - With integrated spectra can discover ejecta-dominated SNRs, measure ISM abundances

High Resolution Spectroscopy of ISM

Basic idea: high resolution absorption spectroscopy of bright point sources

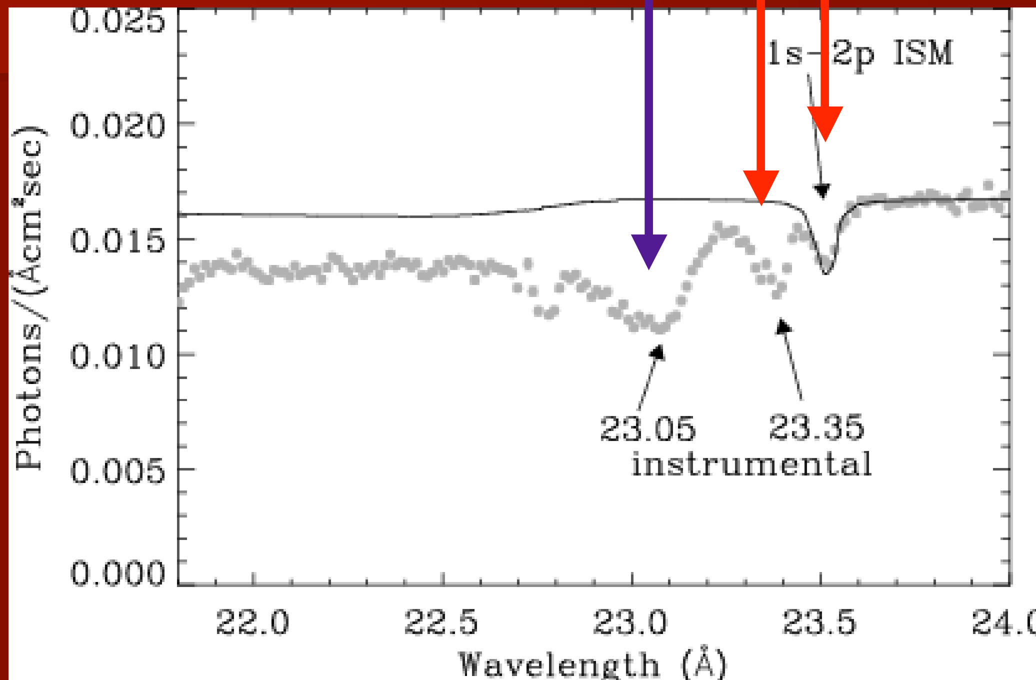
Shape and absolute wavelength of photoelectric absorption edges and lines sensitive to ionization state and chemical environment of absorbing species ('chemical shift'); **typical shifts of order eV's**

Photoelectric absorption cross section for absorption by atoms in environment with short-range order exhibits characteristic quantum interference effect: 'XAFS' (X-ray Absorption Fine Structure)

In principle a single sensitive X-ray absorption spectrum with a few eV resolution can address all the physical chemistry of the major constituents of the ISM as well as the properties of the dust along the line of sight. Will be limited by effective area.

Oxygen 1s-2p; atomic and molecular

Oxygen K edge



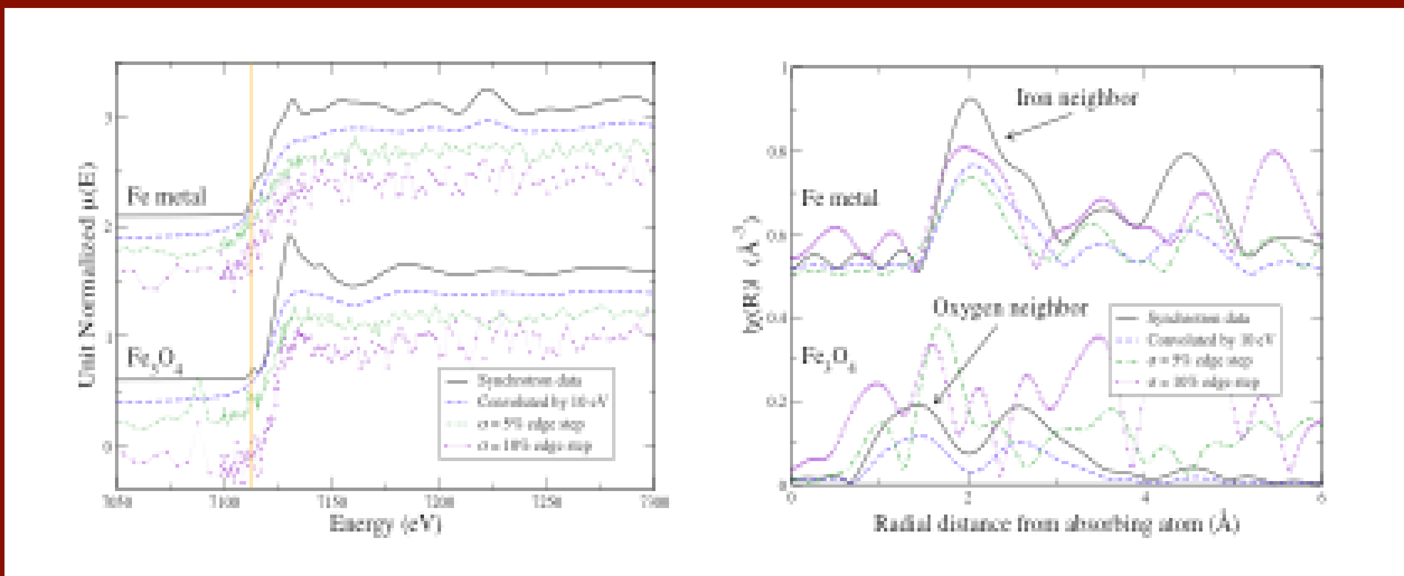
XMM RGS spectrum of two low-ISM absorption sources (Mkn 421, PKS2155-304): ISM, instrument.

(De Vries et al., 2003, *Astron. Astrophys.*, 404, 959)

Possible first detection in astrophysical source:

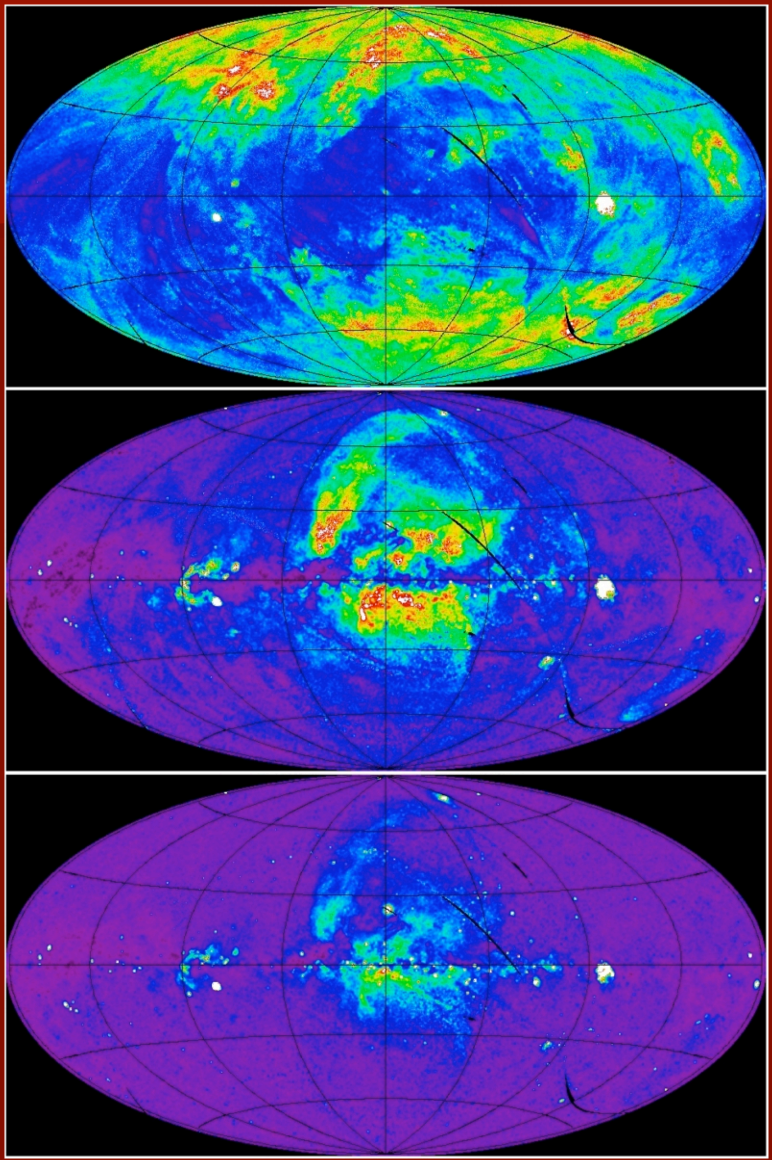
GRS1915 (Lee *et al.*, 2002)/*Chandra* HETGS; technique in extensive use in condensed matter physics

Need lots of light: example: Fe K XAFS



(Lee & Ravel, 2004 preprint)

Galactic Diffuse Emission (Soft)



_ kev RASS image (top) – contributions from many local components forming large loops and structures

3/4 kev RASS image (middle) – more uniform background, absorption by the Galactic plane, contributions from individual sources

1.5 kev RASS image (bottom) – similar to previous

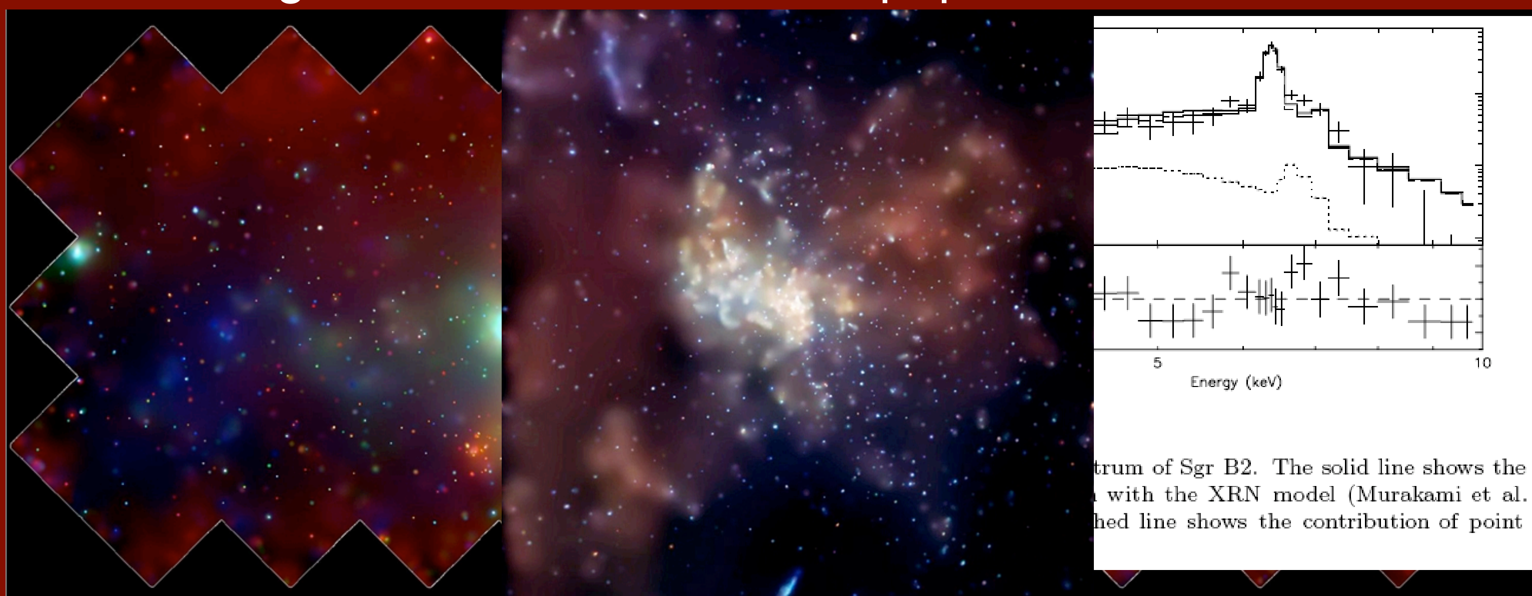
Science goals: understand hot phase of ISM, find evidence for galactic outflows or “chimneys”

Galactic Diffuse Emission (Hard)

Above 2 keV the Galactic ridge, bulge and center become visible in emission.

The Galactic ridge emission appears spectrally as a hot thermal bremsstrahlung with lines from highly ionized Si, S, Ar, Ca, and Fe. Its precise origin is still unknown.

The Galactic center, as revealed by Chandra, is extremely rich and complex containing SNRs, a possible reflection nebula (Sgr B2), Sgr A*, swarming black holes, and a new population of faint hard sources



Galactic Diffuse Req't

- Low background
- Field of view
- Ability to raster scan/mosaic
- Significant effective area (nondispersive) below 0.5 keV (~500 cm^2 at 0.15 keV)
- SXT PSF – to study/remove pt sources

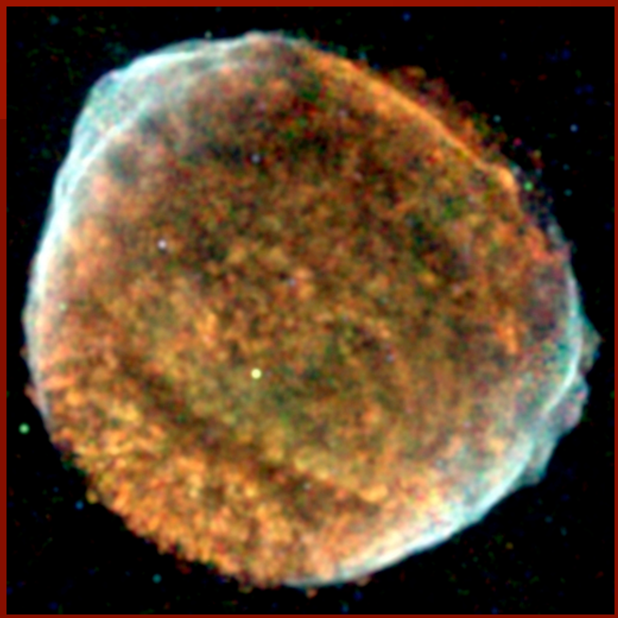
Constellation-X Capabilities: Requirements for SNR studies

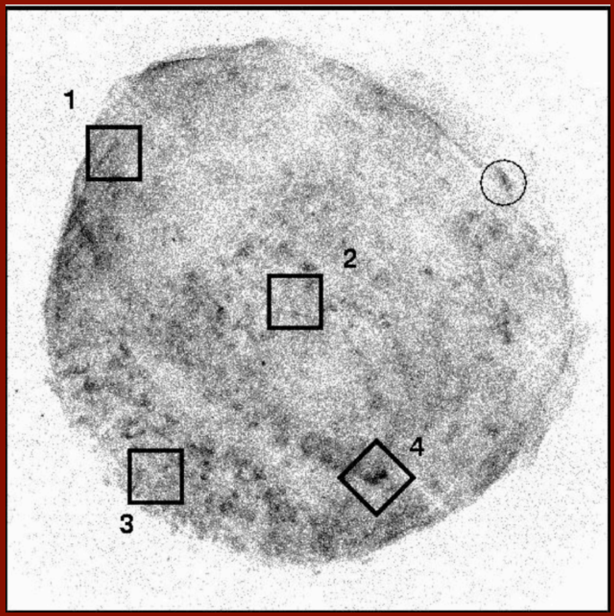
- SXT PSF
  - <5” (Cas A, LMC SNRs, diffuse Galactic emission, Galactic center knots)
- Spectral resolution (nondispersive)
  - <2 eV for E<8 keV (velocities, line broadening
- Spectral resolution (dispersive)
  - R>1000 (3000 optimal) ISM/IGM absorption
- Non X-ray background (E<1.5 keV)
  - At or below the level of the unresolvd cosmic XRB (diffuse Galactic emission)
- Non X-ray background (E>1.5 keV)
  - At or below the level of the unresolvd cosmic XRB (abundances in large SNRs, diffuse emission)
- Effective area
  - Con-X baseline – limited to studying extragalactic SNRs no further than M31 and M33
- Effective area (nondispersive, E<0.5 keV)
  - 500 cm^2 at 0.15 keV (diffuse Galactic emission)

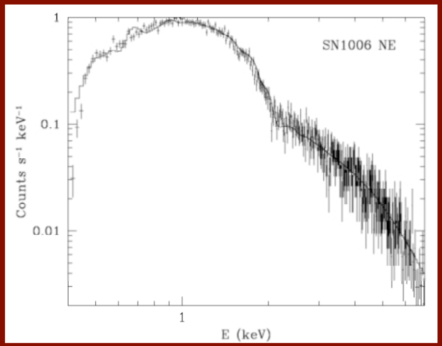
Constellation-X Capabilities: Requirements for SNR studies

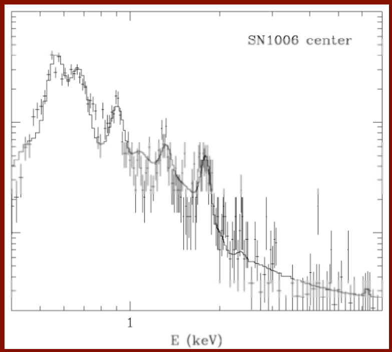
- Field of view
  - Sufficient to subtract background from pt srces (total area should be 5x area covered by an unresolved source)
  - Enhanced FoV should not come at the expense of effective area
  - Larger FoV wth lower CCD-typ resolution not useful
- Raster scans/mosaicing/large numbers of multiple pointings
  - Must be implemented efficiently (large SNRs, diffuse emission)
- High count rate tolerance
  - 3000 counts/s in 2.5’ square region (bright part of Cas A)
- Rapid response for ToO over large sky area
  - Observe SN Ia <2 days after discovery
  - Bright SN Ia rare events: need large sky coverage (>50% for 2 total)
- HXT effective area
  - Extend band to beyond ~80 keV
- HXT PSF (1’), FoV (no smaller than SXT)

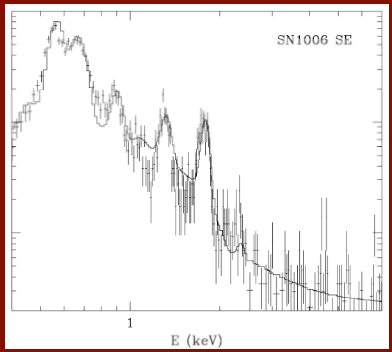
SN1006 – Line Studies

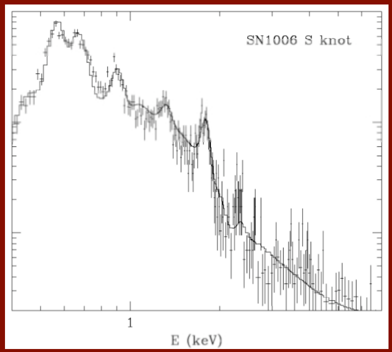




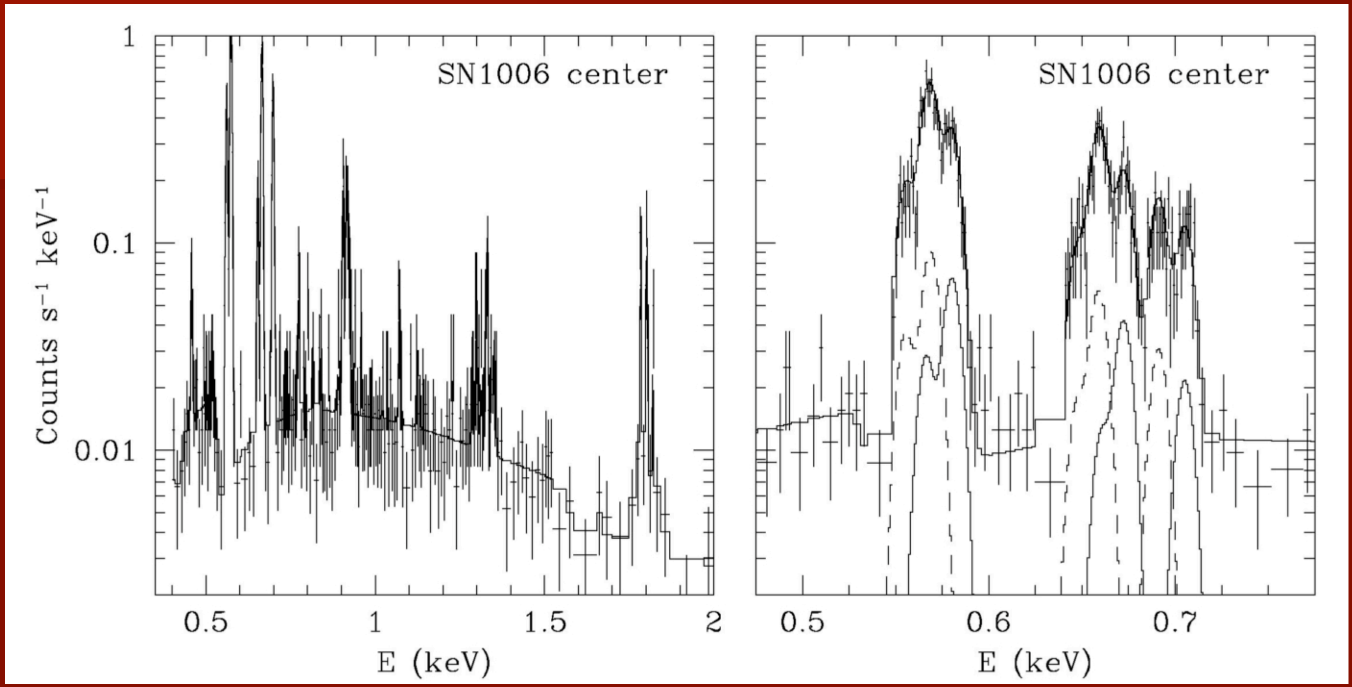








SN1006 – Line Studies



- Simulation of center (40 ks, 15”x15”)
- Expansion speeds of +/- 3000 km/s (front and back shells) and intrinsic line width of 3.5 eV